Transverse Spin Physics

Lecture I

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The plan:

- **Lecture I:**

  Transverse spin structure of the nucleon
  Overview of past experiments
  History of interpretation
  Overview of present understanding

- **Lecture II**

  Transverse Momentum Dependent distributions (TMDs)
  Sivers function
  Twist-3

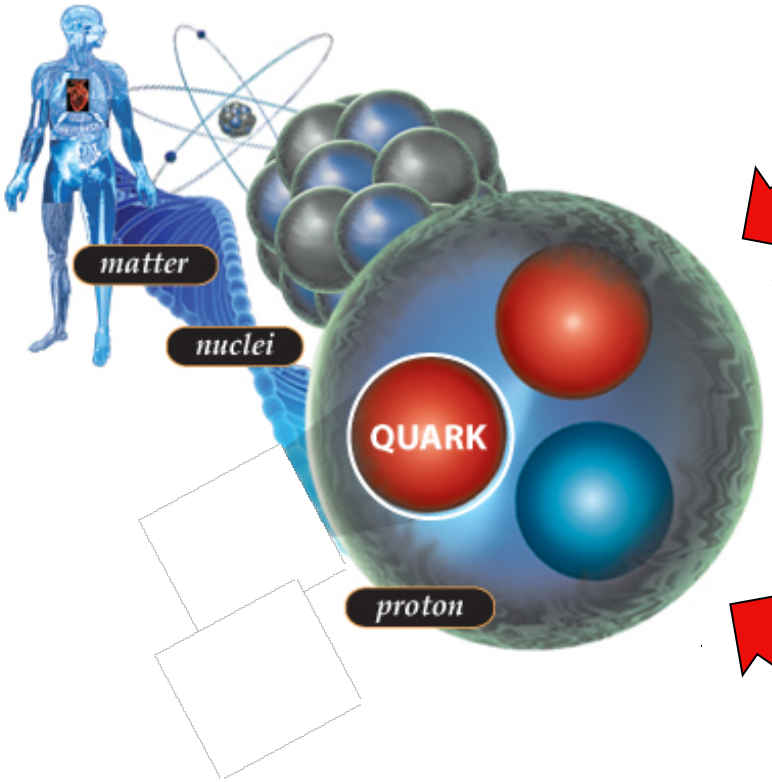
- **Lecture III**

  Transversity
  Collins Fragmentation Function
  Global analysis

- **Lecture IV**

  Evolution of TMDs

Exploring the nucleon: a fundamental quest

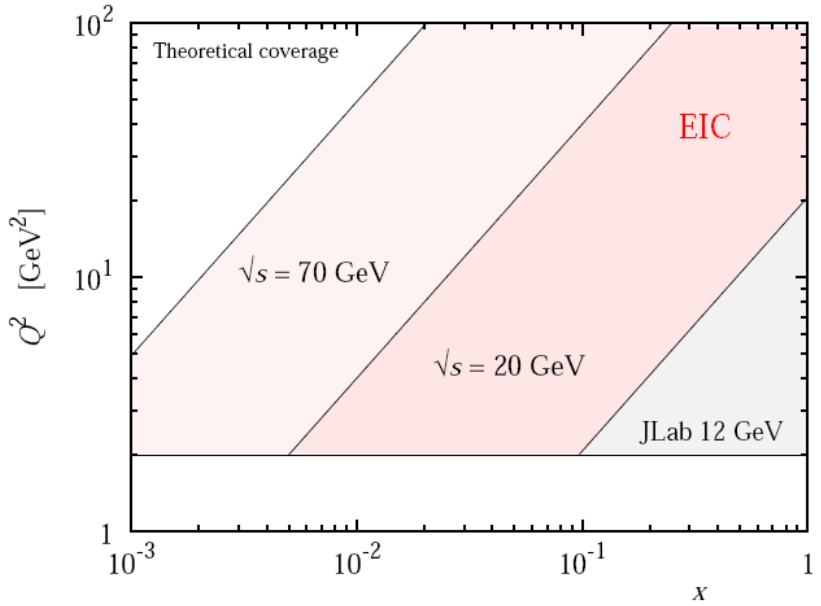


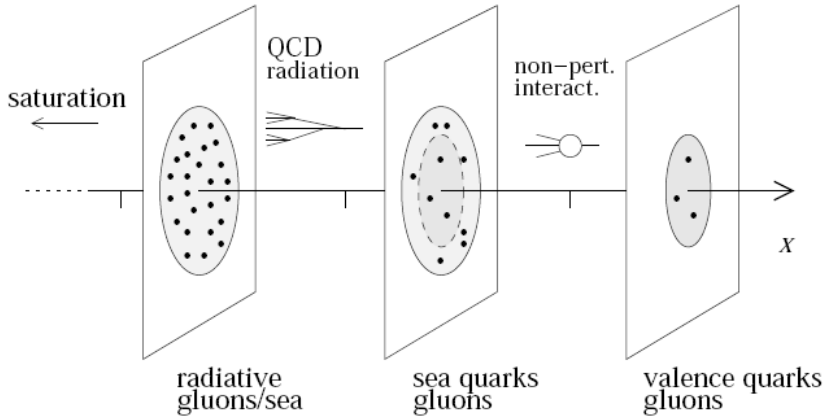
Know what we are made of !

Understand the strong force: "QCD"

Use protons as tool for discovery (e.g. LHC)

Nucleon landscape





Nucleon is a many body dynamical system of quarks and gluons

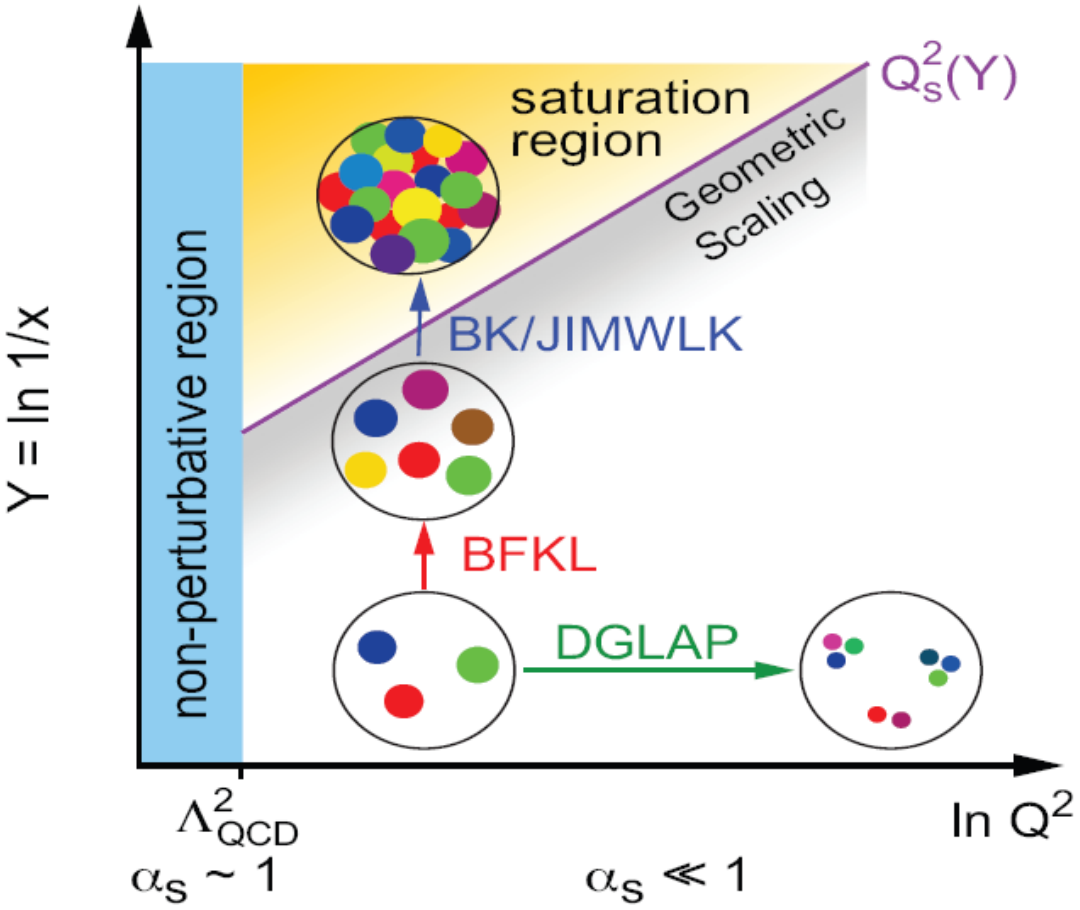
Changing x we probe different aspects of nucleon wave function

How **partons move** and how they are distributed in **space** is one of the future directions of development of nuclear physics

Technically such information is encoded into Generalised Parton Distributions and Transverse Momentum Dependent distributions

These distributions are also referred to as **3D (three-dimensional) distributions**

Nucleon landscape



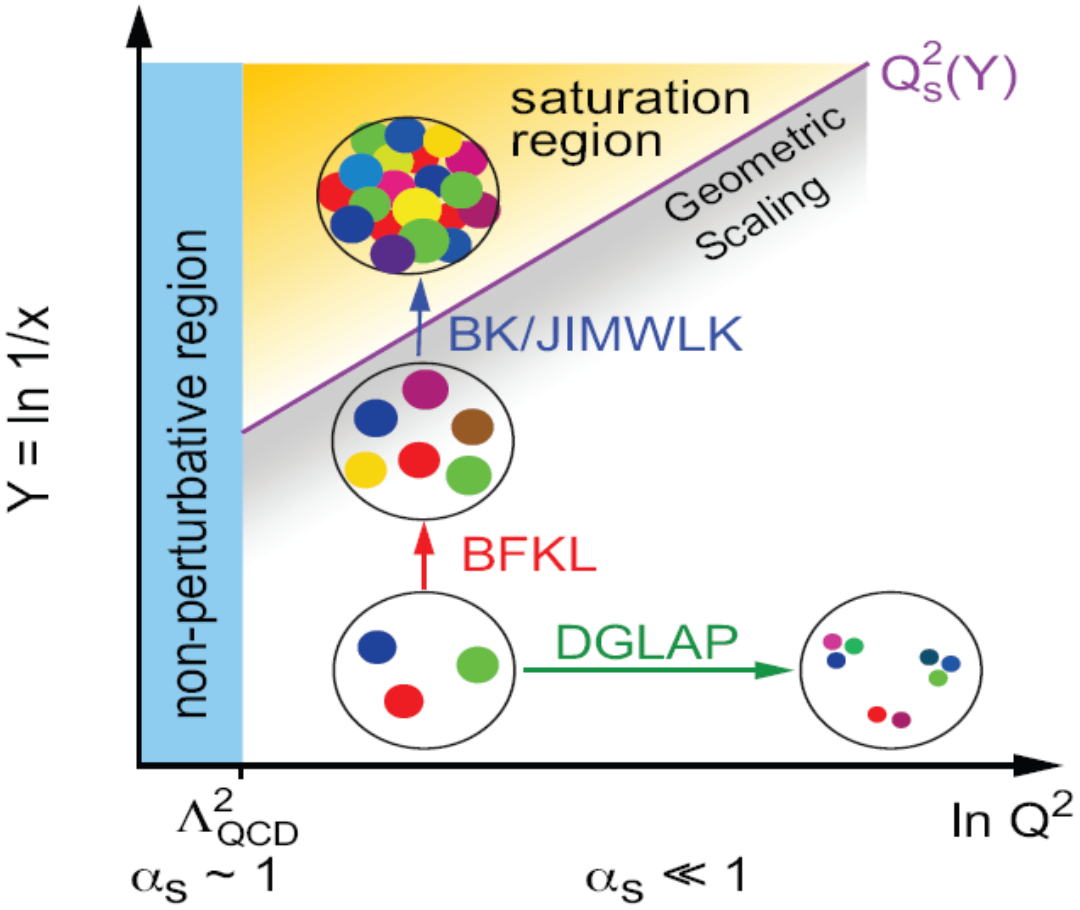
Virtual photon serves as a microscopic probe of the nucleon:

Larger Q^2 probe smaller distances – DGLAP evolution

$$\lambda \sim 1/Q$$

Plot from EIC whitepaper

Nucleon landscape

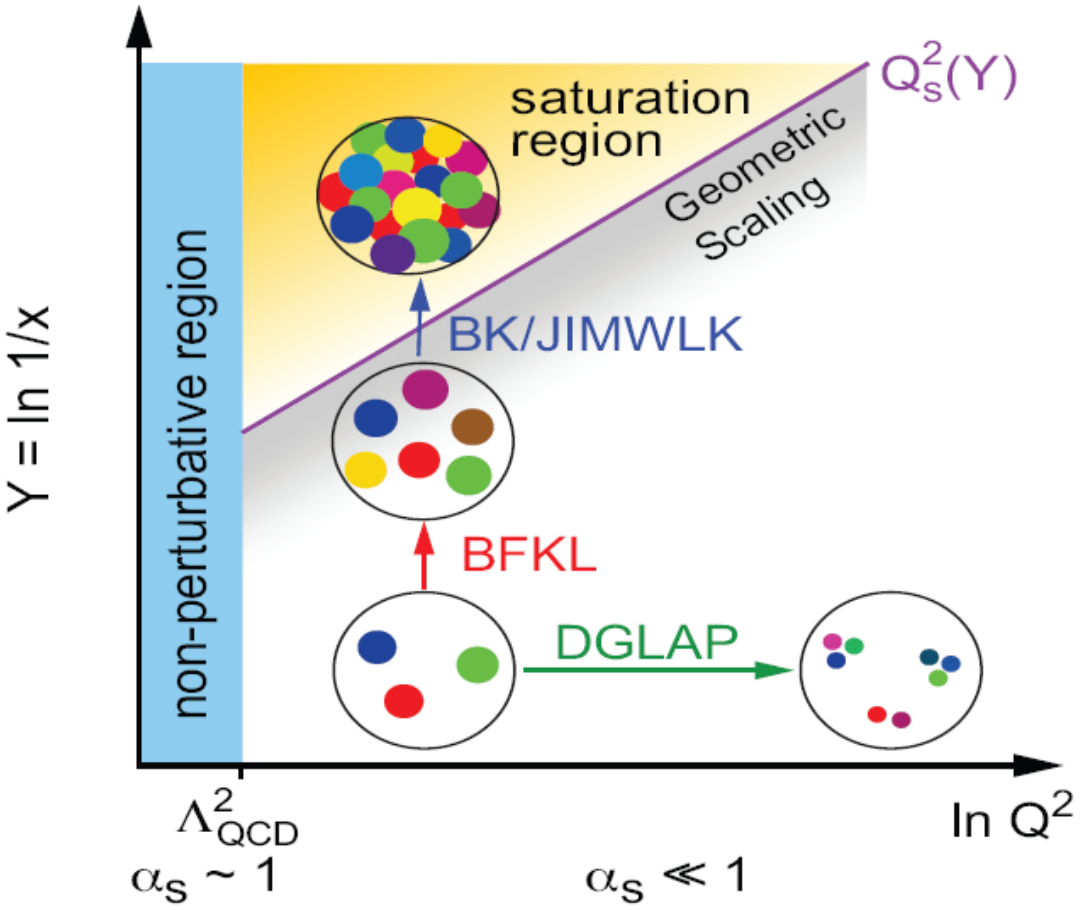


Virtual photon serves as a microscopic probe of the nucleon:

Fixing Q^2 and changing the energy we probe BFKL evolution

Plot from EIC whitepaper

Nucleon landscape



Virtual photon serves as a microscopic probe of the nucleon:

Recombination of gluons leads to non linear effects – BK/JIMWLK evolution and phenomenon of saturation. Dilute vs dense regime of QCD.

Plot from EIC whitepaper

Spin and QCD

"Experiments with spin have killed more theories than any other single physical parameter"

Elliot Leader, Spin in Particle Physics, Cambridge U. Press (2001)

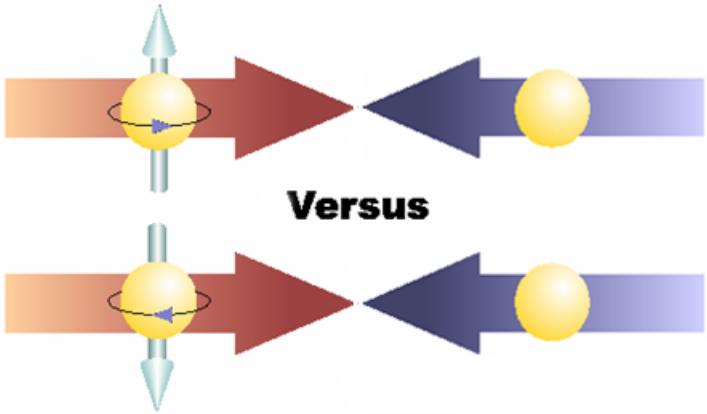
"Polarisation data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection."

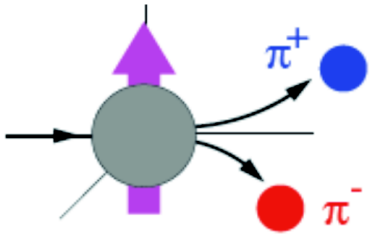
J. D. Bjorken, Proc. Adv. Research Workshop on QCD Hadronic Processes, St. Croix, Virgin Islands (1987).

History

Spin and QCD

Consider A_N in hadron hadron collision:



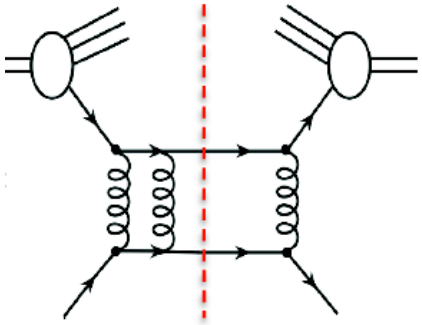


$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Spin and QCD

QCD had a very simple prediction:

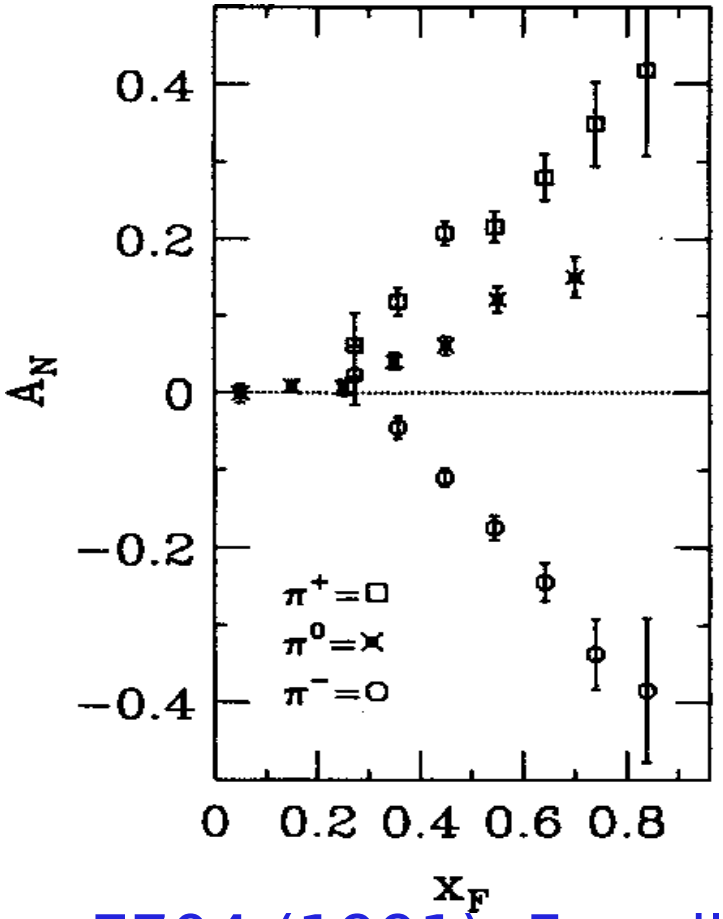
Helicity flip is proportional to the small mass of the quark, thus



$$\propto \alpha_s \frac{m_q}{p_T} \qquad A_N \simeq 0.001$$

Kane, Pumplin and Repko (1978)

Experiment proved this prediction wrong



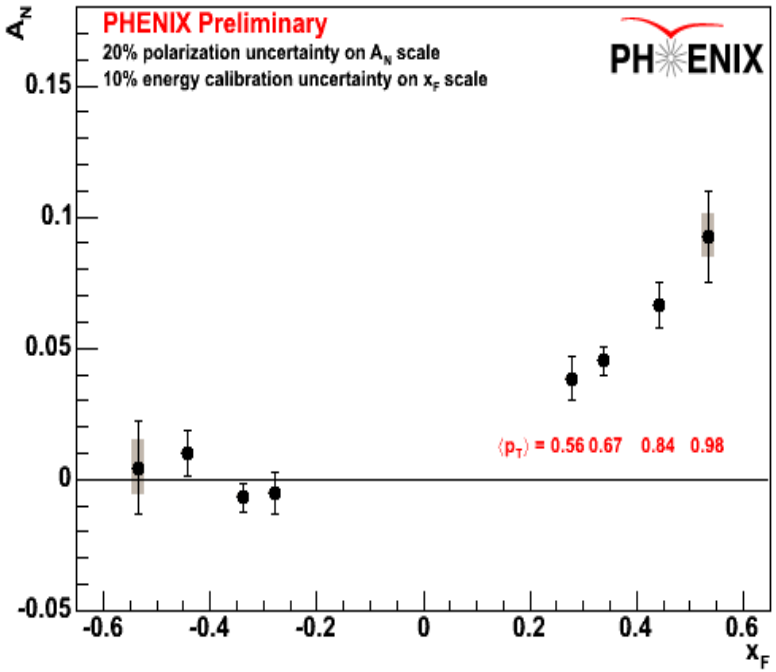
E704 (1991), Fermilab

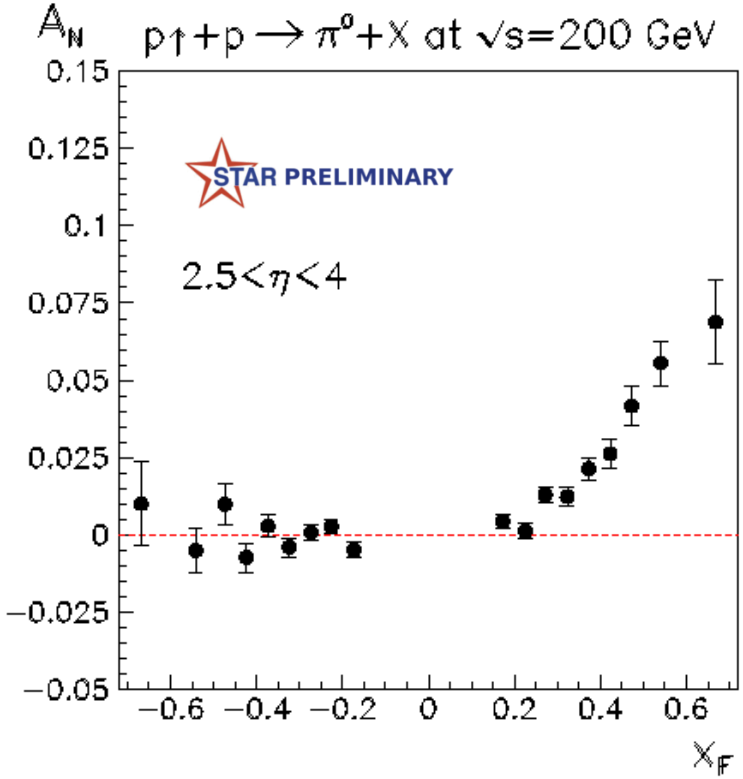
$$A_N \simeq 40\%$$

$$\sqrt{s} = 19.1\ (GeV)$$

Asymmetry survives with energy

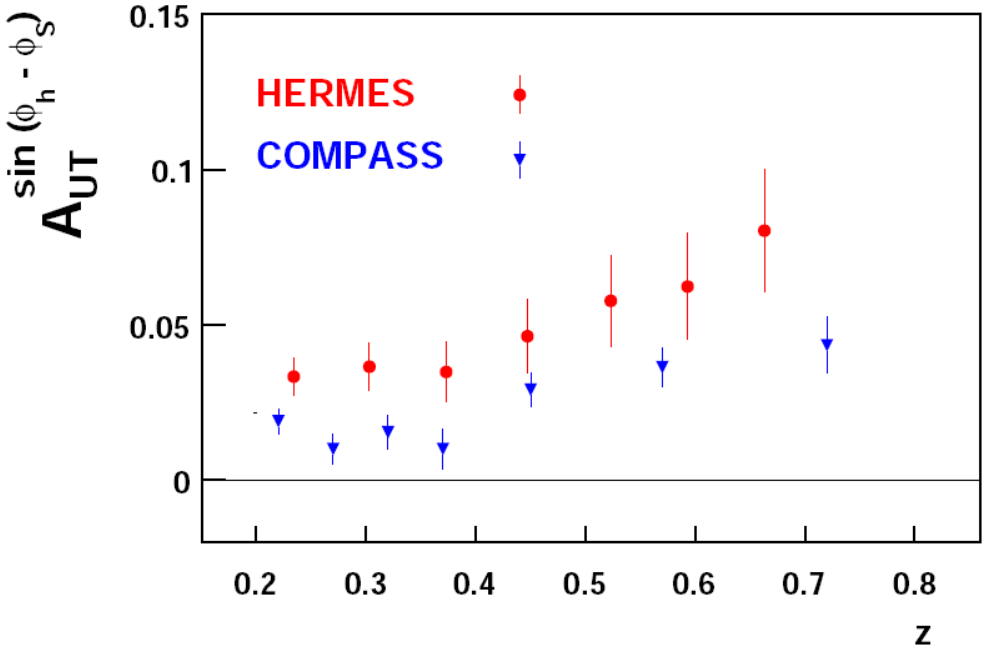
$\sqrt{s} = 62$ GeV





RHIC: STAR, BRAHMS and PHENIX

Asymmetry survives with energy



HERMES and COMPASS

Failure of QCD?

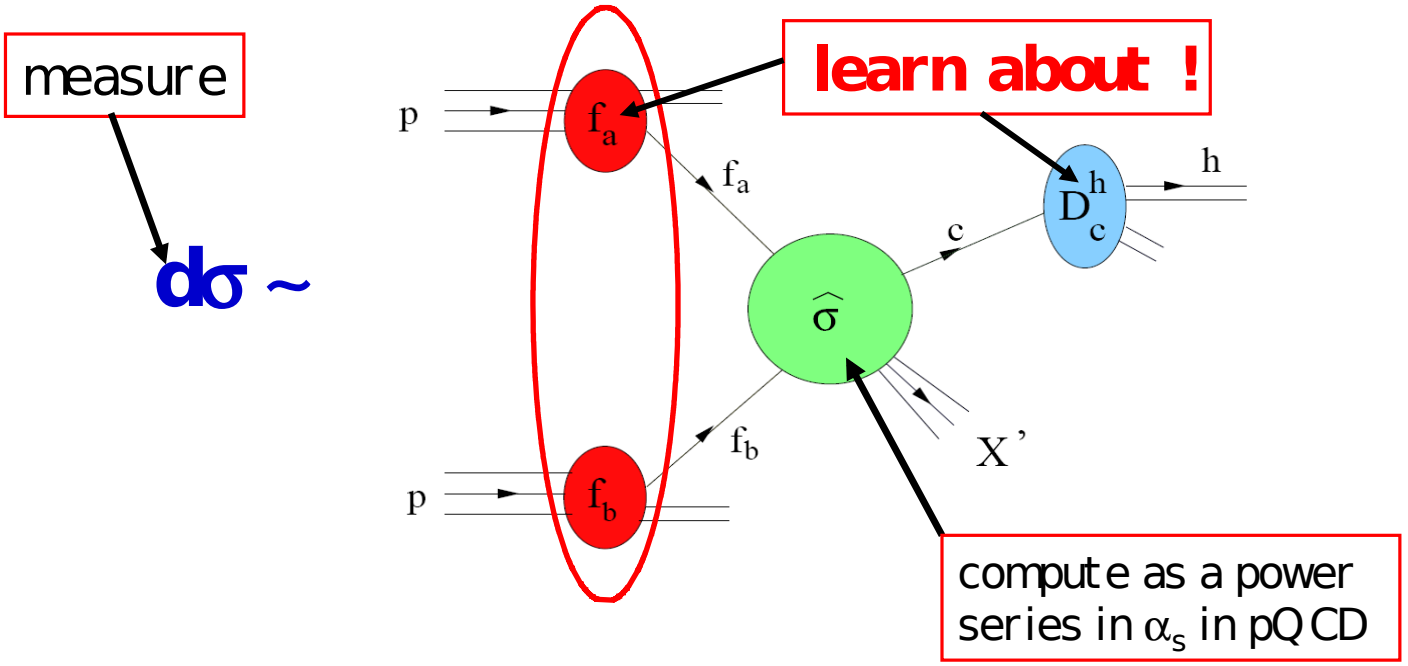
Not at all: better understanding of QCD

Not at all: better understanding of QCD

History of understanding

QCD factorization

- Factorization of short-distance and long-distance physics

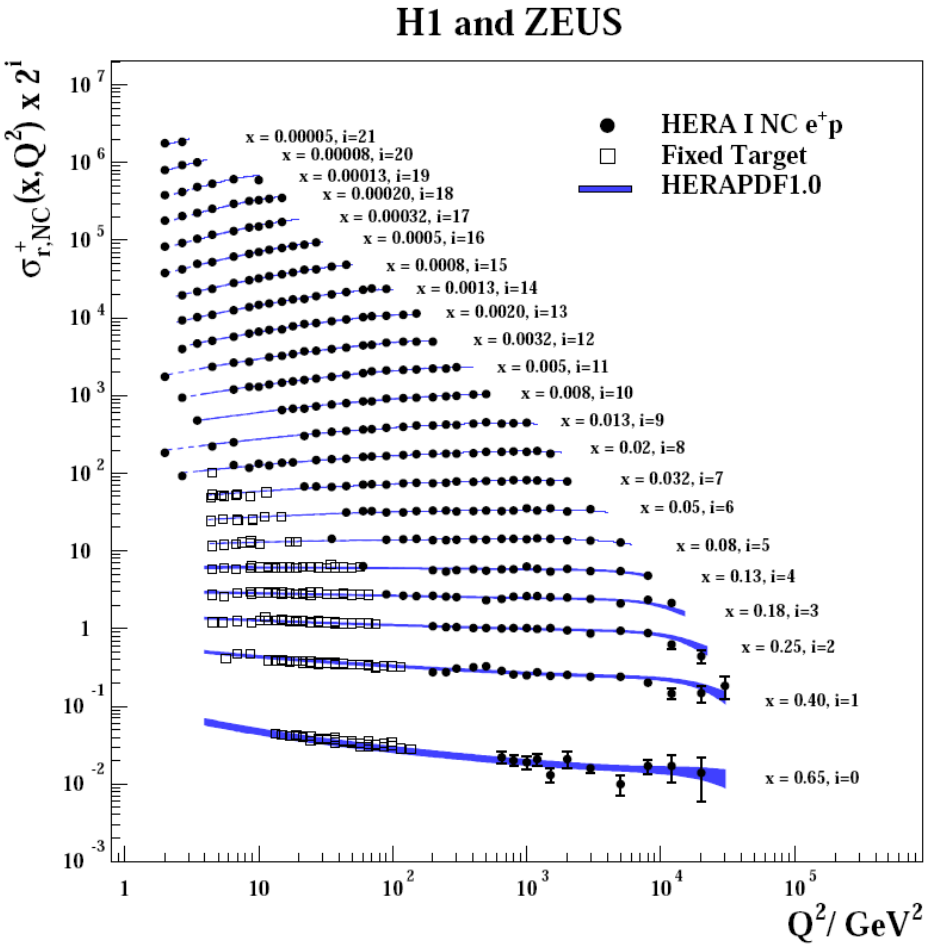


$$\sigma(P_h, S) \propto f_a(x_a, \mu^2) \otimes f_b(x_b, \mu^2) \otimes \hat{\sigma}_{ab\to c} \otimes D_{h/c}(z_c, \mu^2)$$

Universal Universal calculable Universal

Success of QCD factorization

- Universality of PDFs: mapped in one process (say DIS), used in other process



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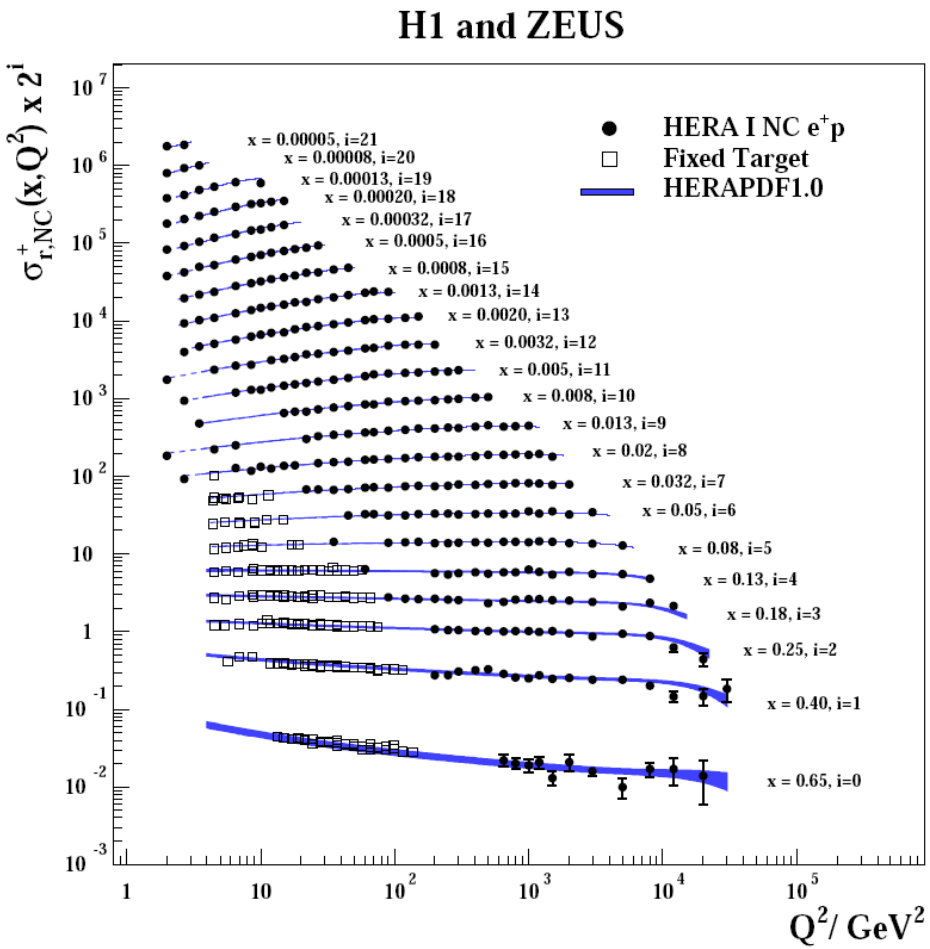

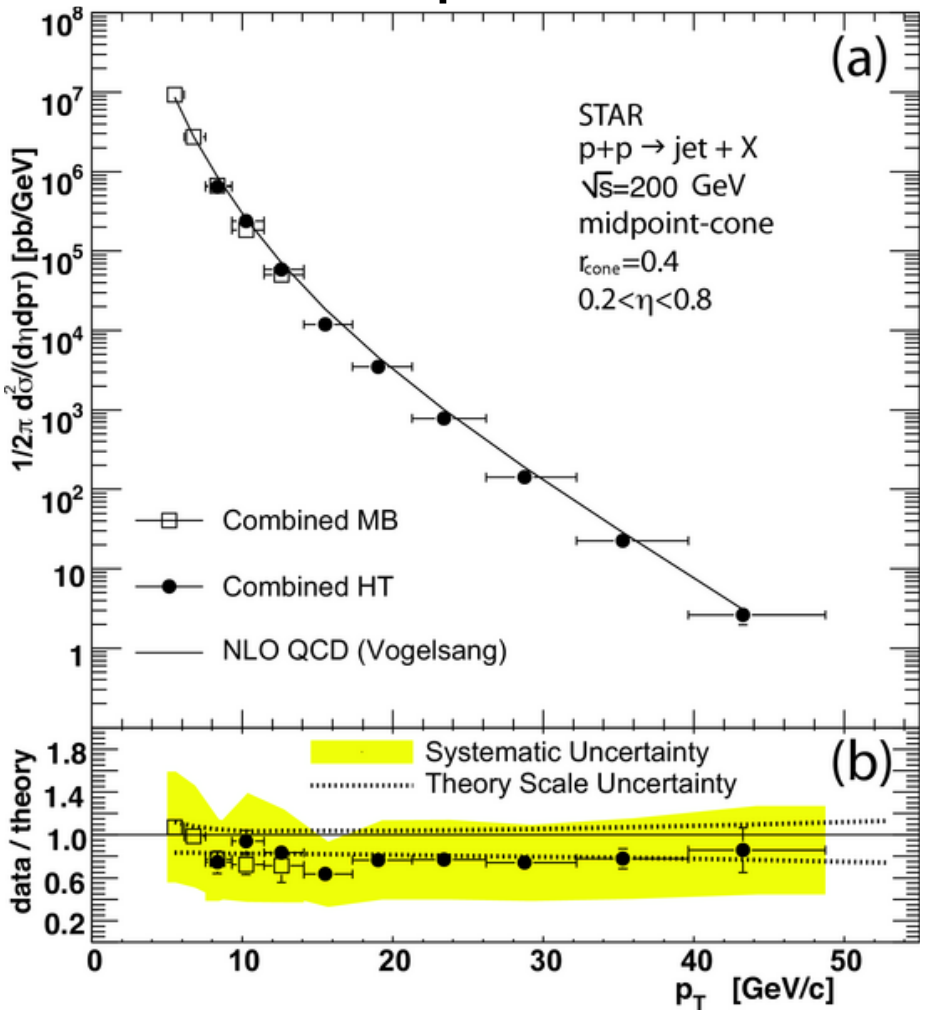

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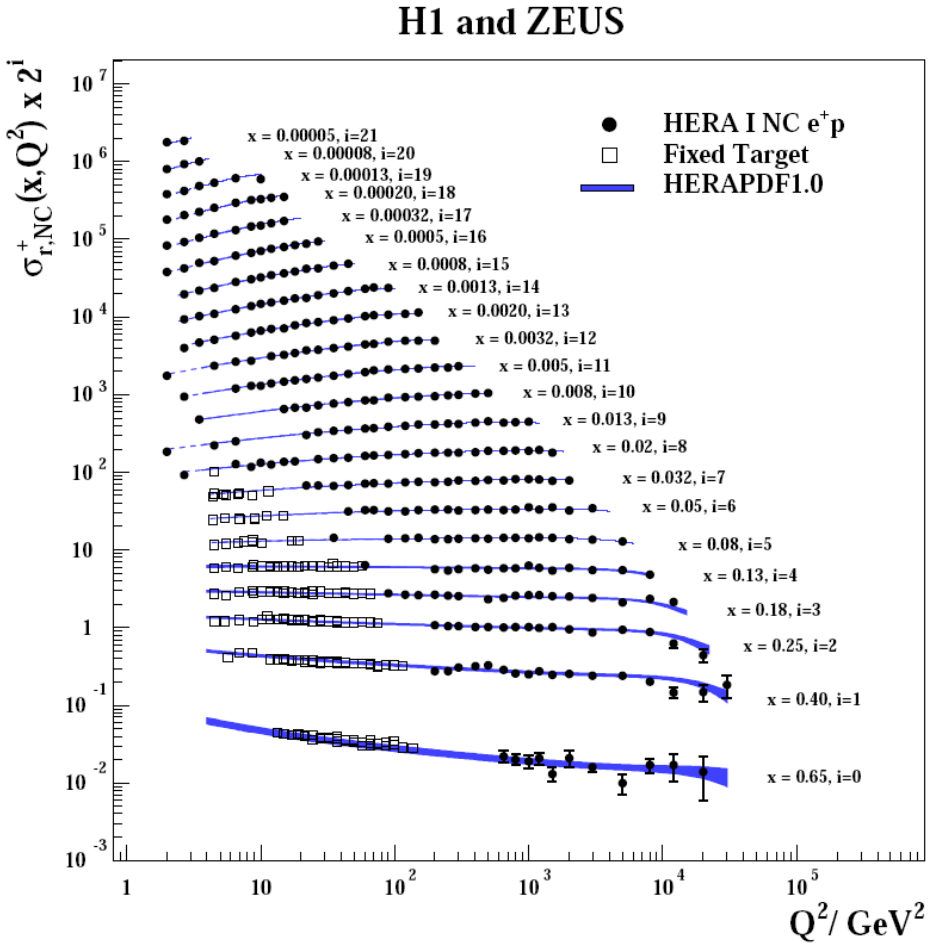

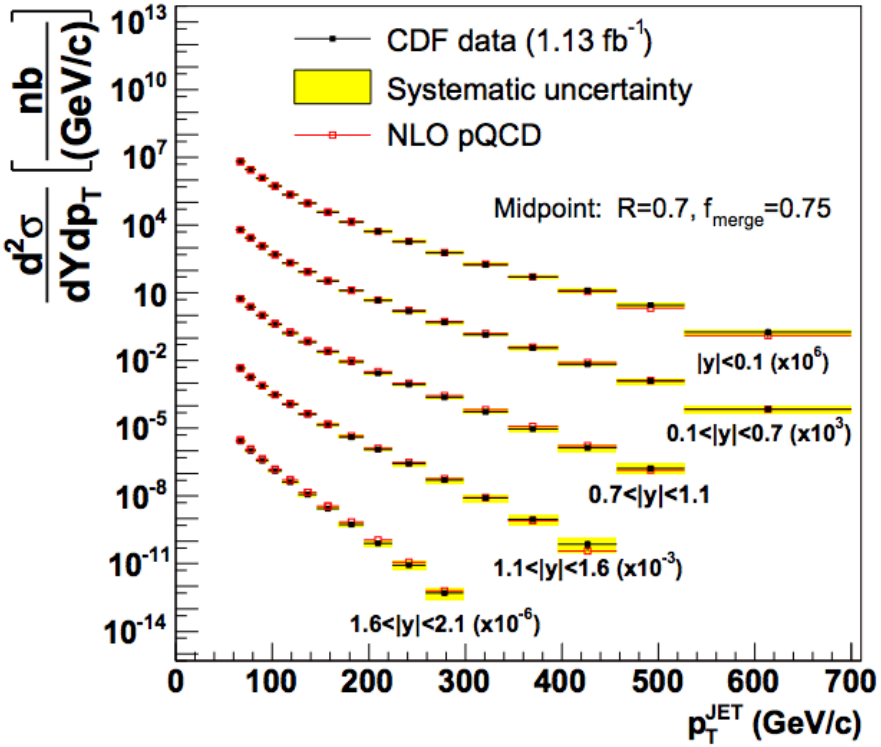

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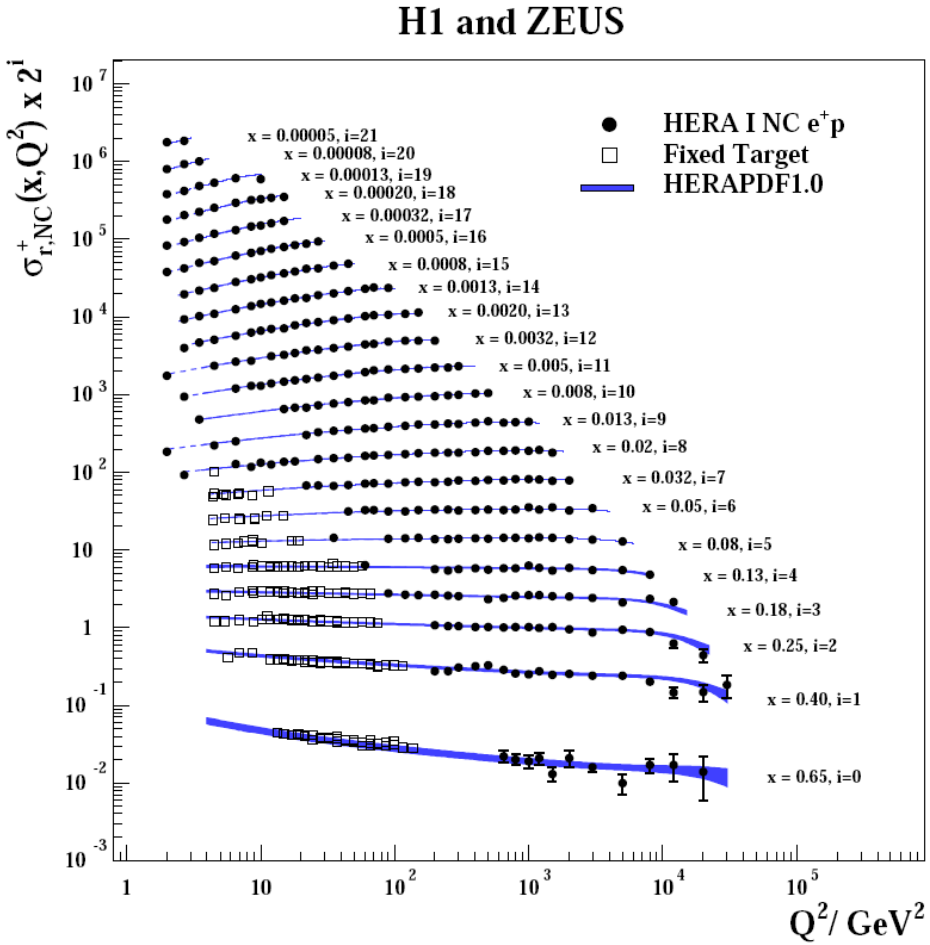
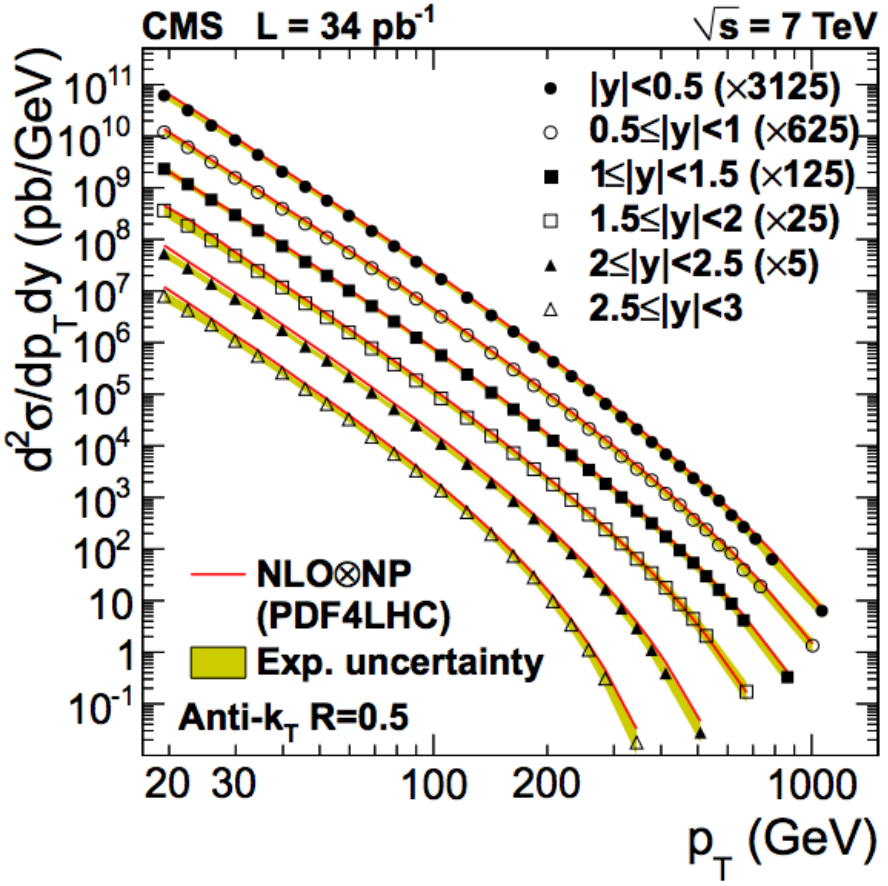




The birth of TMDs (as phenomenological quantities): D. Sivers, PRD 41 (1990) 83

1990

$$G_{a/p}(x;\mu^2) \rightarrow G_{a/p}(x,\boldsymbol{k}_T;\mu^2)$$

The relevance of the transverse momentum for the asymmetry can be seen from the venerable Chou-Yang[1] model of the constituent structure of a transversely polarized proton. If we assume a correlation between the spin of the proton and the orbital motion of its constituents, Chou and Yang showed the existence of a nontrivial A_N in elastic scattering. The coherent dynamics which correlates the spin of the proton with the orbital angular momentum of the quarks and gluons can also produce a constituent-level asymmetry in transverse momentum:

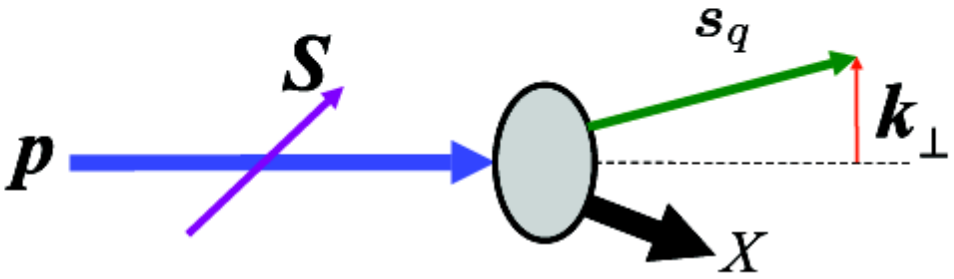
$$\Delta^N G_{a/p(\uparrow)}(x,\boldsymbol{k}_T;\mu^2) = \sum_h \left[G_{a(h)/p(\uparrow)}(x,\boldsymbol{k}_T;\mu^2) - G_{a(h)/p(\downarrow)}(x,\boldsymbol{k}_T;\mu^2)\right]$$
$$= \sum_h \left[G_{a(h)/p(\uparrow)}(x,\boldsymbol{k}_T;\mu^2) - G_{a(h)/p(\uparrow)}(x,-\boldsymbol{k}_T;\mu^2)\right]$$

1 T. T. Chou and C. N. Yang, Nucl. Phys. B107, 1 (1976)

Anselmino, Transversity 2014

$$A_N \left[E\frac{d^3\sigma}{d^3p}(pp_\uparrow \to mX) \right] \simeq \sum_{ab\to cd} \int d^2\boldsymbol{k}_T^a\, dx_a \int d^2\boldsymbol{k}_T^b\, dx_b \int d^2\boldsymbol{k}_{TC} \frac{dx_c}{x_c^2} \Delta^N G_{a/p_\uparrow}(x_a, k_T^a; \mu^2)$$
$$\times\, G_{b/p}(x_b, k_T^b; \mu^2)\, D_{m/c}(x_c, k_T^c : \mu^2) \times \tilde{s}\, \frac{d\sigma}{d\tilde{t}}(ab \to cd)\, \delta(\tilde{s} + \tilde{t} + \tilde{u})$$

.... this equation corresponds to a probabilistic formula in the original spirit of the parton model where the unknown soft nonperturbative dynamics have been absorbed into the specification of the density $\Delta^N G$ ...



Sivers function

$$f_{q/p,\boldsymbol{S}}(x, \boldsymbol{k}_\perp) = f_{q/p}(x, k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x, k_\perp)\, \boldsymbol{S} \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp)$$
$$= f_{q/p}(x, k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x, k_\perp)\, \boldsymbol{S} \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp)$$

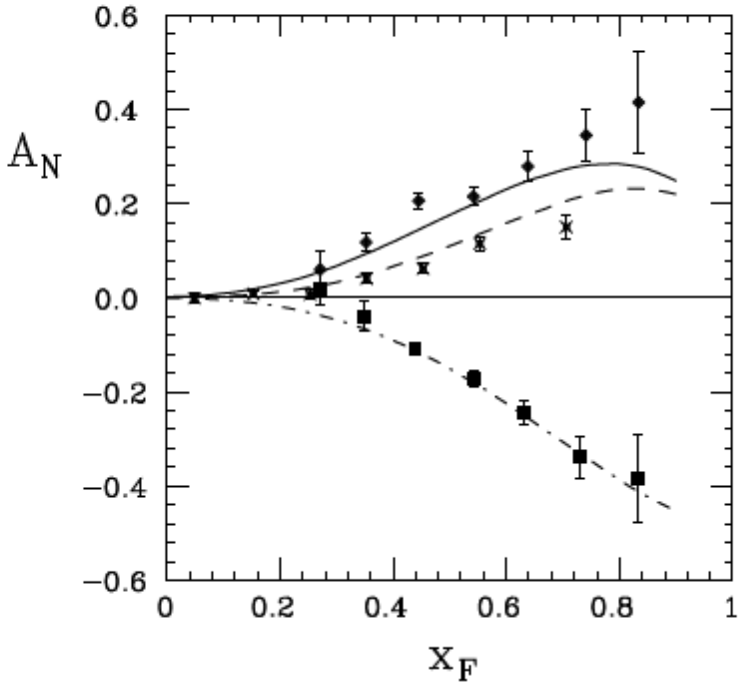
Anselmino, Transversity 2014

early A_N phenomenology with Sivers function

(M.A., M. Boglione and F. Murgia, PL B 362 (1995) 164)

$$\frac{E_\pi\, d\sigma^{p^\uparrow p\to\pi X}}{d^3\boldsymbol{p}_\pi} \sim \frac{1}{2}\sum_{a,b,c,d}\sum_{\lambda_a,\lambda'_a;\lambda_b;\lambda_c,\lambda'_c;\lambda_d}\int d^2\boldsymbol{k}_{\perp a}dx_a\,dx_b\,\frac{1}{z}$$

$$\rho^{a/p^\uparrow}_{\lambda_a,\lambda'_a}\,\hat{f}_{a/p^\uparrow}(x_a,\boldsymbol{k}_{\perp a})\,f_{b/p}(x_b)\,\hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}\,\hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda_b}\,D^{\lambda_c,\lambda'_c}_{\pi/c}(z)$$



Anselmino, Transversity 2014

Asymmetry comes from modulation of the initial distribution function (D.Sivers 1990)

Asymmetry comes from modulation in final state fragmentation (J.Collins 1993)

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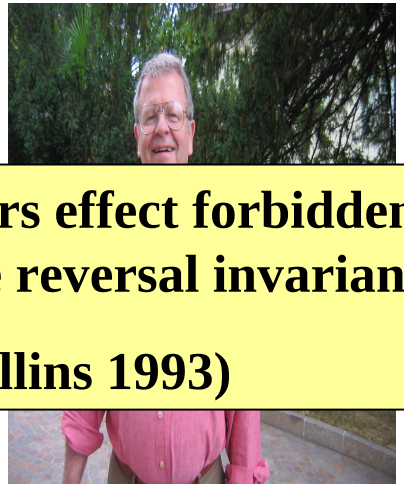
Asymmetry comes from modulation in final state fragmentation (J.Collins 1993)



Sivers effect forbidden by time reversal invariance

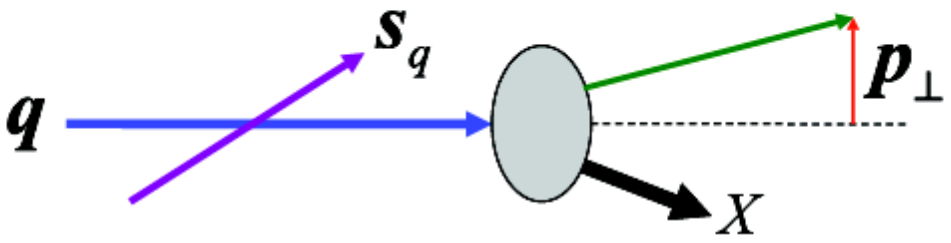
(Collins 1993)

Sivers suggested that the $k_\perp$ distribution of the quark could have an azimuthal asymmetry when the initial hadron has transverse polarization. However, such an asymmetry is prohibited because QCD is time-reversal invariant....

Collins fragmentation function

Nucl. Phys. B396 (1993) 161

It is shown that the azimuthal dependence of the distribution of hadrons in a quark jet is a probe of the transverse spin of the quark initiating the jet. This results in a new spin-dependent fragmentation function that acts at the twist-2 level.



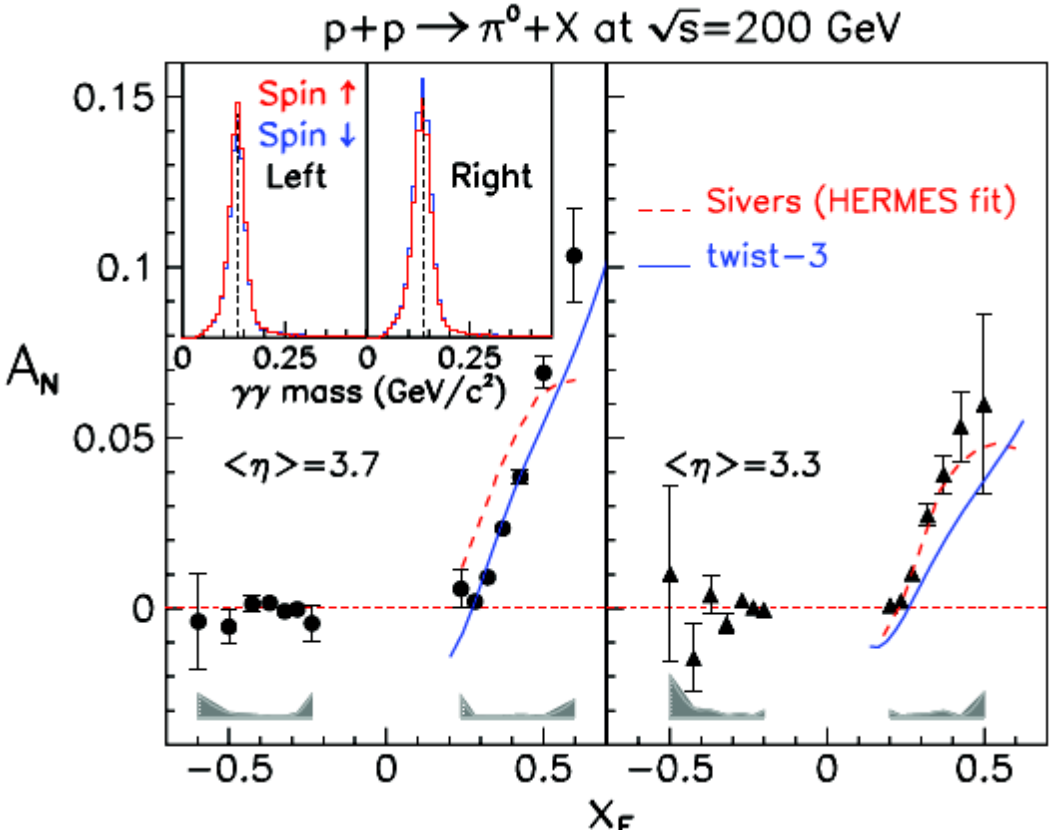
Collins function

$$D_{h/q,\boldsymbol{s}_q}(z,\boldsymbol{p}_\perp) = D_{h/q}(z,p_\perp) + \frac{1}{2}\Delta^N D_{h/q^\uparrow}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$
$$= D_{h/q}(z,p_\perp) + \frac{p_\perp}{zM_h}H_1^{\perp q}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$

Anselmino, Transversity 2014

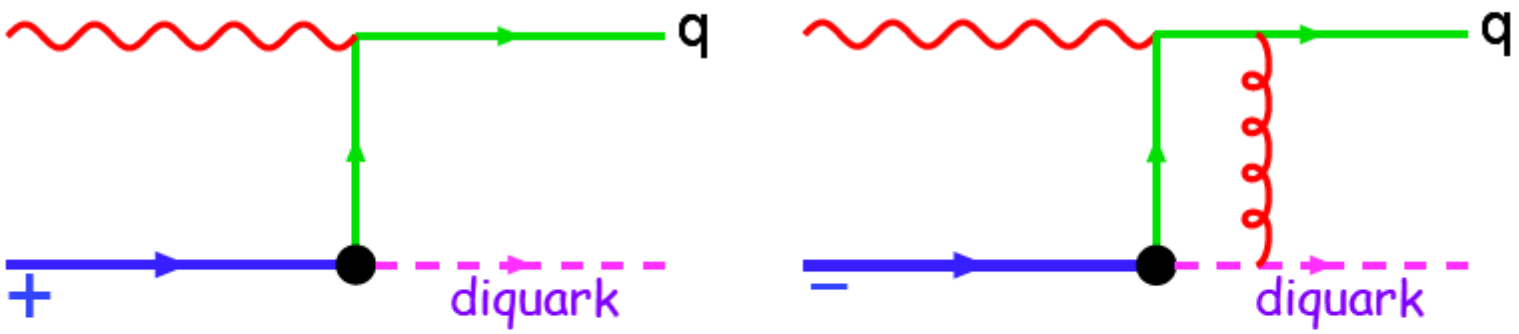
Phenomenology never stopped...

Prediction od AN with Sivers effect



gauge links have physical consequences; quark models for non vanishing Sivers function,

SIDIS final state interactions



Brodsky, Hwang, Schmidt, PL B530 (2002) 99 - Collins, PL B536 (2002) 43

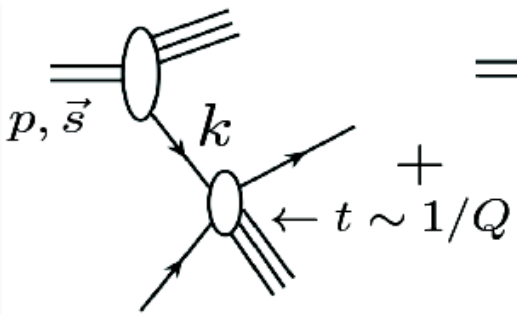
An earlier proof that the Sivers asymmetry vanishes because of time-reversal invariance is invalidated by the path-ordered exponential of the gluon field in the operator definition of parton densities. Instead, the time-reversal argument shows that the Sivers asymmetry is reversed in sign in hadron-induced hard processes (e.g., Drell-Yan), thereby violating naive universality of parton densities. Previous phenomenology with time-reversal-odd parton densities is therefore validated.

$$[f_{1T}^{q\perp}]_{\rm SIDIS} = -[f_{1T}^{q\perp}]_{\rm DY}$$

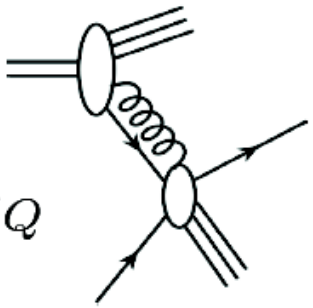
Another way to explain the asymmetry

Twist-3

$$\sigma(Q,\vec{s}) \propto \left| \right.$$



$$+$$



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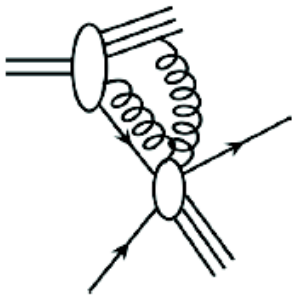


$$+ \cdots \left. \right|^2$$

Multi parton correlations contribute to the cross section.

These correlations are called
Efremov-Teryaev-Qiu-Sterman matrix elements,
They appear at twist-3 level in cross section.

$$\sigma = \sigma^{LT} + \frac{Q_s}{Q}\sigma^{HT} + \ldots$$

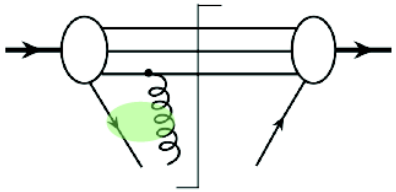
$$= H^{LT} \otimes f_2 \otimes f_2 + \frac{Q_s}{Q} H^{HT} \otimes f_3 \otimes f_2 + \ldots$$

If only one large scale is present in the process, then

$$A_N \propto \sigma(p_T, S_\perp) - \sigma(p_T, -S_\perp)$$
$$\propto T^{(3)}(x, x, S_\perp) \otimes \hat{\sigma}_T \otimes D(z) + \delta q(x, S_\perp) \otimes \hat{\sigma}_D \otimes D^{(3)}(z, z) + \ldots$$

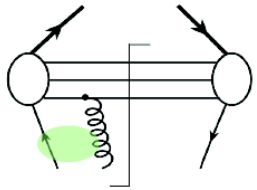
Leading power cancels

Twist-3 parton correlation functions

$T^{(3)}(x, x, S_\perp) \propto$ 

Qiu-Sterman 1991

Twist-3 parton fragmentation functions

$D^{(3)}(z, z) \propto$ 

Kang, Yuan, Zhou 2010

No probability interpretation!

TMD formalism:

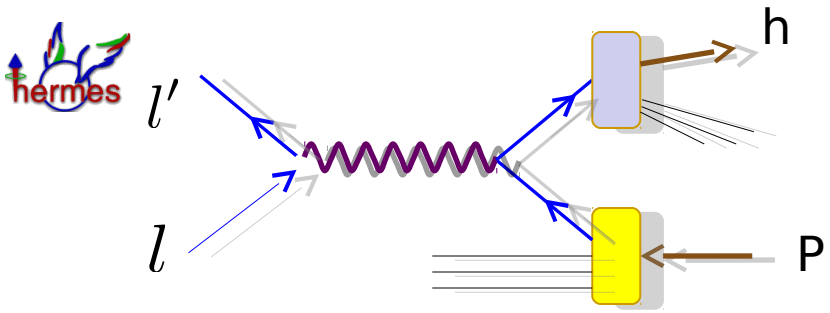
Sivers, Collins effects, other functions

Twist-3 functions:

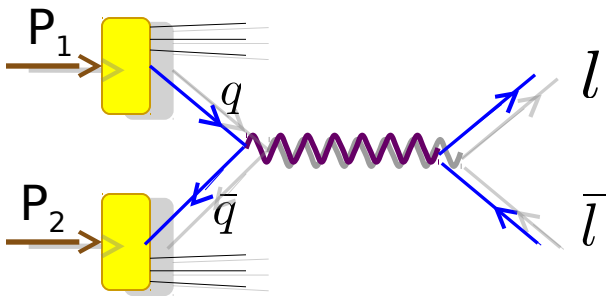
Qiu-Sterman matrix elements

Are these two formalisms “competing” with each other?
Are there relations between these functions?

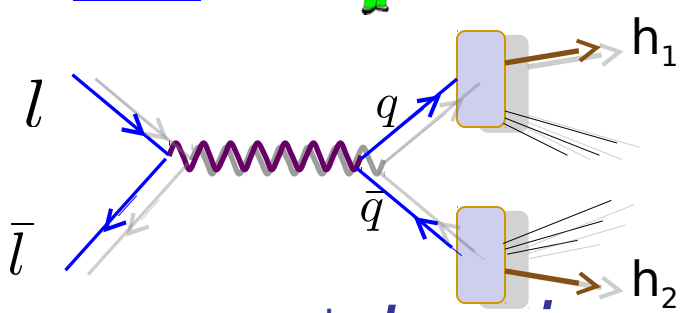
Other experiments, other processes:



SIDIS



Drell-Yan



e^-e^+ to pions

hard scattering

+

Partonic Fragmentation

Partonic Distributions

Modern view on hadron structure

I: relation of TMD and Twist-3

TMD

Two observed scales

$Q_1 \sim \Lambda_{QCD}$ sensitive to parton's transverse motion

$Q_2, \ldots \gg \Lambda_{QCD}$ ensures pQCD

$$f(x, k_\perp; Q^2)$$

TMD distributions

Collinear

One observed momentum scale

$$Q_1, Q_2, \ldots \gg \Lambda_{QCD}$$

$$f(x; Q^2)$$

Collinear distributions

TMD

Collinear

TMD distributions

$$f(x, k_\perp; Q^2)$$

Evolution CSS

Collins Soper Sterman 1985
Ji Ma Yuan 2004
Collins 2011

Collinear distributions

$$f(x; Q^2)$$

Evolution DGLAP

TMD

Collinear

TMD distributions

$$f(x, k_\perp; Q^2)$$

Evolution CSS

Collins Soper Sterman 1985
Ji Ma Yuan 2004
Collins 2011

$f(x; Q^2)$ is an ingredient with corresponding DGLAP

Collinear distributions

$$f(x; Q^2)$$

Evolution DGLAP

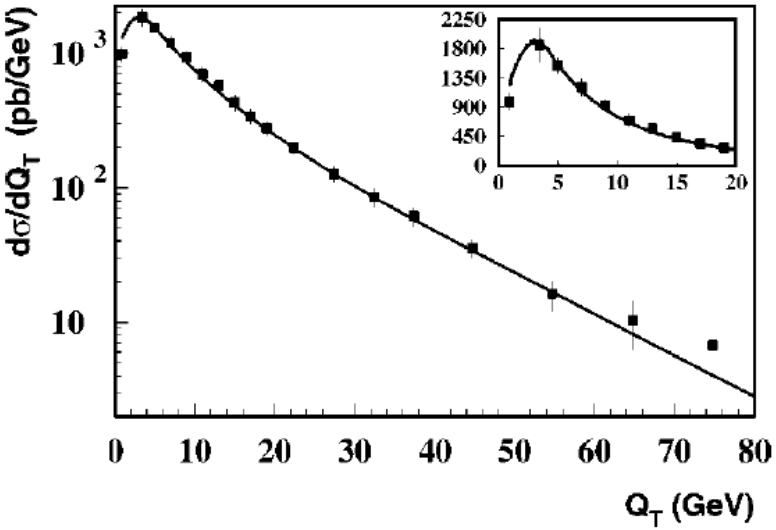
TMD

Collinear

TMD distributions

$$f(x, k_\perp; Q^2)$$

Phenomenology:
A lot of different functions
Mainly LO (tree level) for spin dependent
Very advanced in unpolarised case

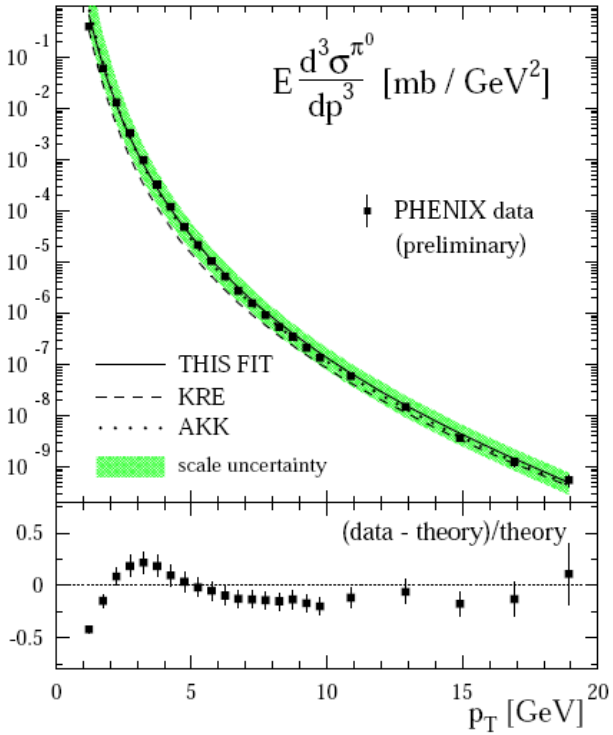


Brock, Landry, Nadolsky, Yuan 2003
Qiu, Zhang 2001

Collinear distributions

$$f(x; Q^2)$$

Phenomenology:
NLO, NNLO ...



De Florian, Sassot, Stratmann 2007
(DSS)

TMD Collinear

TMD distributions

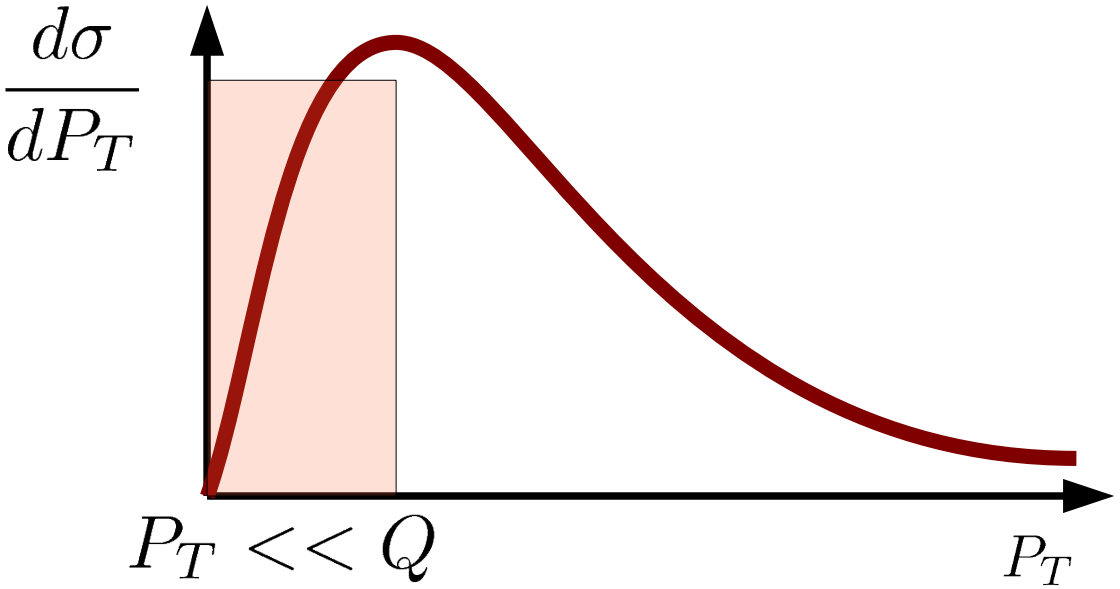
$$f(x, k_\perp; Q^2)$$

Phenomenology:
A lot of different functions

Collinear distributions

$$f(x; Q^2)$$

Beyond leading twist:
Twist-3 matrix elements
Efremov Teryaev (1982), Qiu, Sterman (1991)



Mulders, Tangerman 1995
Boer, Mulders 1998

TMD Collinear

TMD distributions

$$f(x, k_\perp; Q^2)$$

Phenomenology:
A lot of different functions

Collinear distributions

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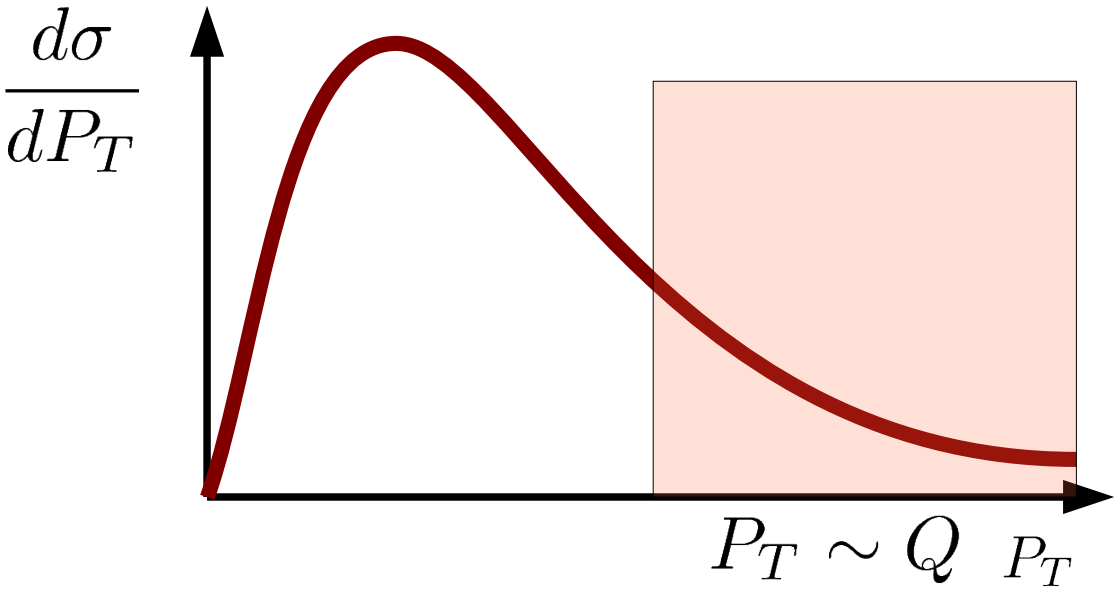


TMD Collinear

TMD distributions

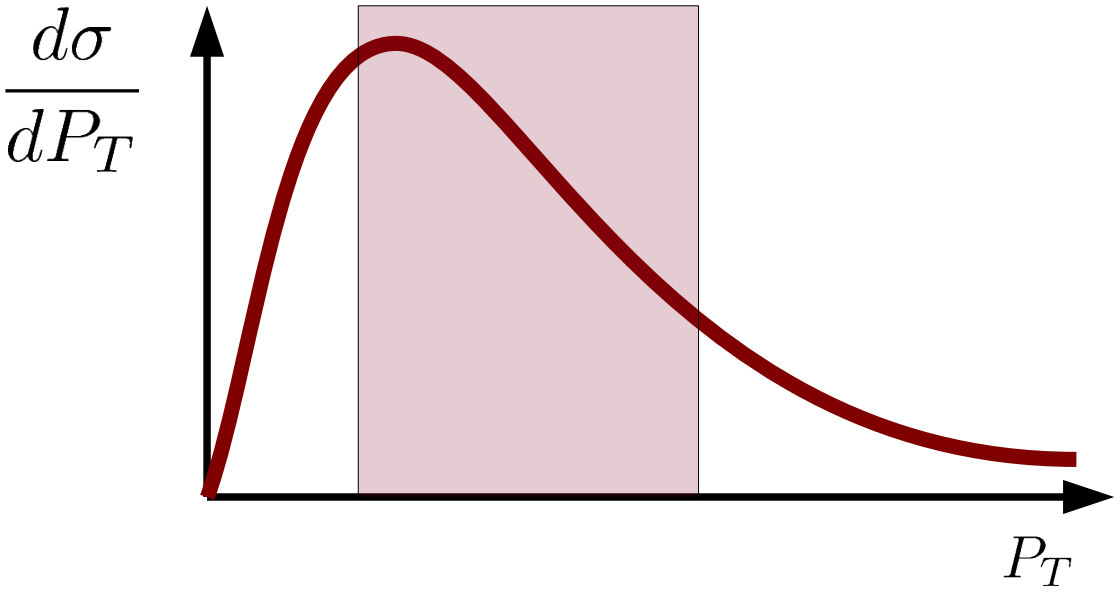
$$f(x, k_\perp; Q^2)$$

Phenomenology:
A lot of different functions

Collinear distributions

$$f(x; Q^2)$$

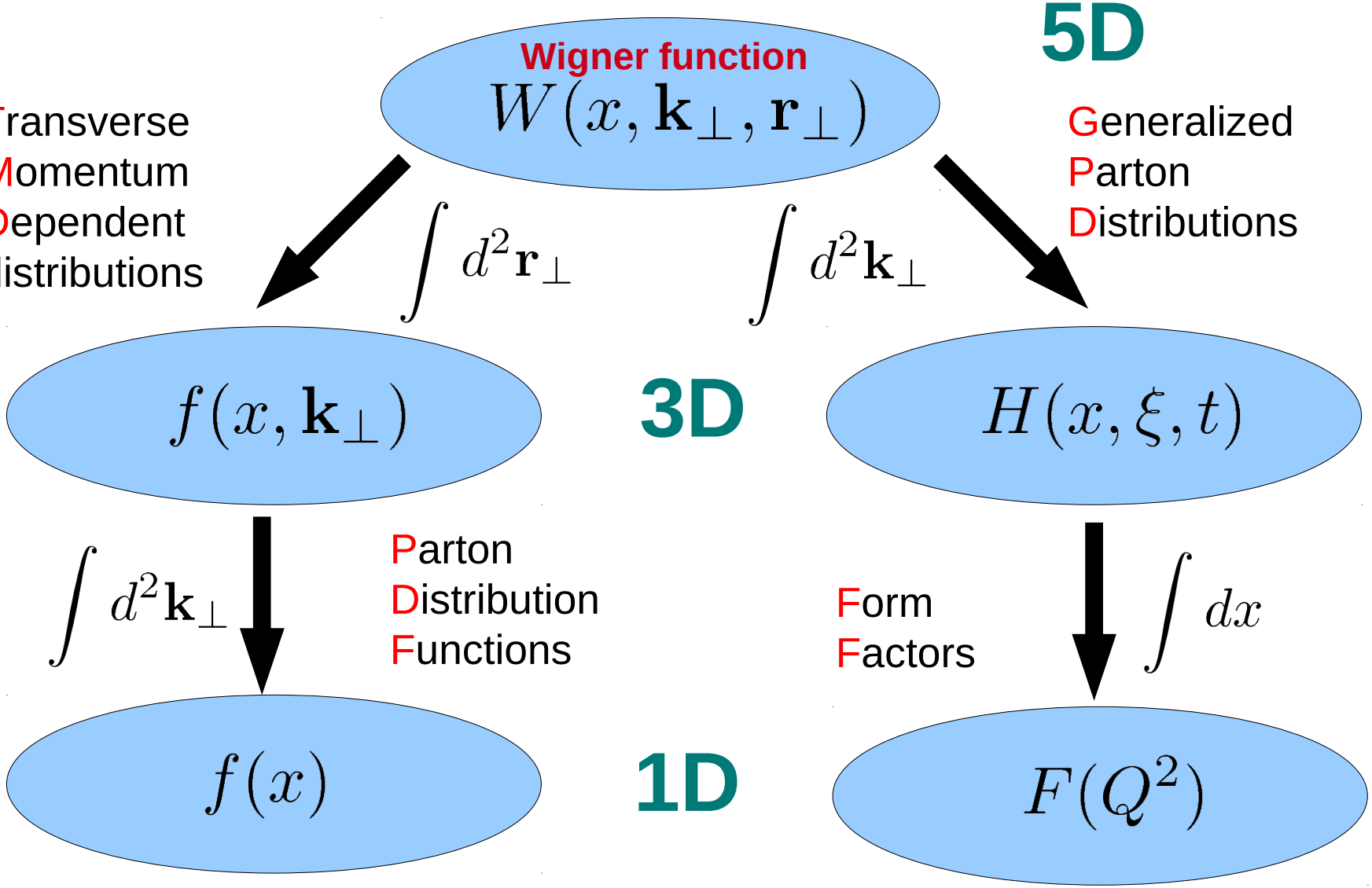
Beyond leading twist:
Twist-3 matrix elements
Efremov Teryaev (1982), Qiu, Sterman (1991)



Intermediate region, both formalisms are applicable and related
Ji, Qiu, Vogelsang, Yuan (2006) etc

II: Generalization of TMD formalism

Unified View of Nucleon Structure



Unified View of Nucleon Structure

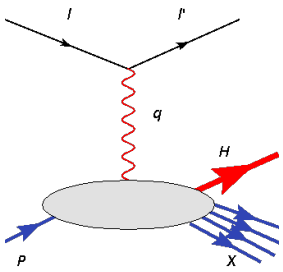
TMD

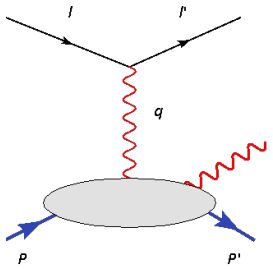
Wigner function

$W(x, \mathbf{k}_\perp, \mathbf{r}_\perp)$

5D

GPD

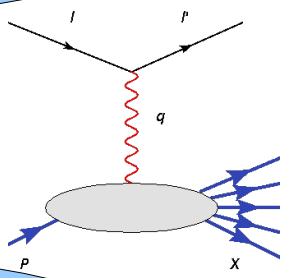


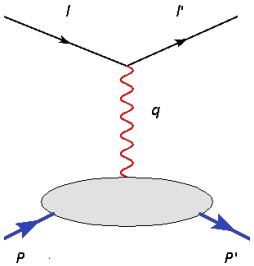


$f(x, \mathbf{k}_\perp)$

3D

$H(x, \xi, t)$





PDF

FF

$f(x)$

1D

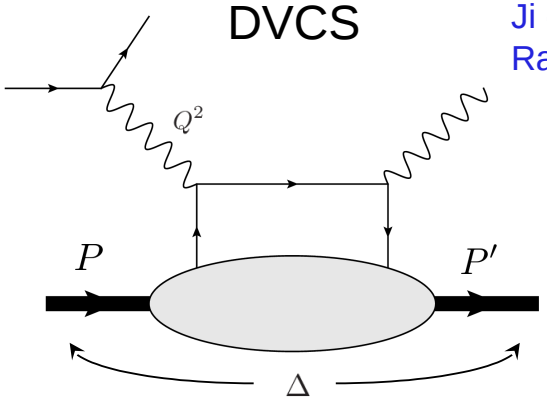
$F(Q^2)$

Particular processes to study. Polarization is required!

GPDs

DVCS

Ji (1997)
Radyushkin (1997)



Q^2 ensures hard scale, pointlike interaction

$\Delta = P' - P$ momentum transfer can be varied independently

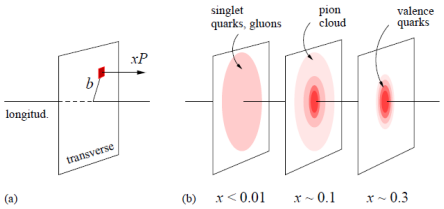
Connection to 3D structure

Burkardt (2000)
Burkardt (2003)

$$\rho(x, \vec{r}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-i\vec{\Delta}_\perp \cdot \vec{r}_\perp} H_q(x, \xi = 0, t = -\vec{\Delta}_\perp^2)$$

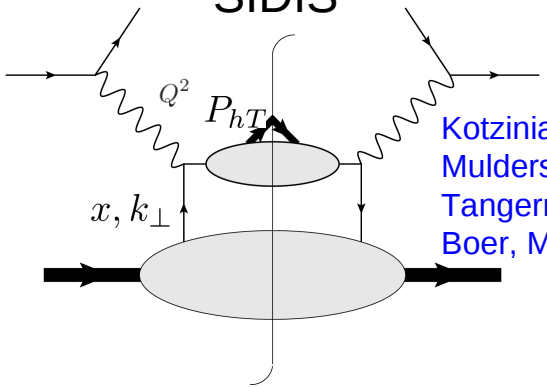
Drell-Yan frame $\Delta^+ = 0$

Weiss (2009)



TMDs

SIDIS



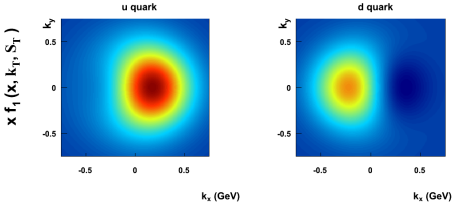
Kotzinian (1995),
Mulders,
Tangerman (1995),
Boer, Mulders (1998)

Q^2 ensures hard scale, pointlike interaction

P_{hT} final hadron transverse momentum can be varied independently

Connection to 3D structure

Ji, Ma, Yuan (2004)
Collins (2011)

$$\tilde{f}(x, \vec{b}_T) = \int d^2k_\perp e^{-i\vec{b}_T \cdot \vec{k}_\perp} f(x, \vec{k}_\perp)$$

AP (2012)